

Article

Economic Implications of Agricultural Land Conversion to Solar Power Production

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Abstract: Meeting greenhouse gas (GHG) reduction targets will require a significant increase in electricity production from sustainable and renewable sources such as solar energy. Farmers have recognized this need as a chance to increase the profitability of their farms by allocating farmland to solar power production. However, the shift from agriculture to power production has many tradeoffs, arising primarily from alternative land uses and other means of production. This paper models the farmers' decision as a constrained profit maximization problem, subject to the amount of land owned by the farmers, who have to allocate it between agriculture and solar power fields, while considering factors affecting production costs. The farmers' problem is nested in the social welfare maximization problem, which includes additional factors such as ecological and aesthetical values of the competing land uses. Empirical analysis using data from a solar field operating in Israel shows that landowners will choose to have solar power production on their land unless agricultural production generates an unusually high net income. Adding the values of non-market services provided by agricultural land does not change this result. The consideration of the reduction in GHG emissions further increases the social welfare from solar fields.



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Keywords: renewable energy production; agricultural land; profit maximization; social welfare; greenhouse gas emissions; landscape; biodiversity

1. Introduction

Anthropogenic climate change due to greenhouse gas (GHG) emissions requires a shift in many areas of human activities. Keeping in mind that most of today's operations rely on power supply, one of the highest priority areas where change is needed is electric power production. This change requires a shift in production from fossil fuels to renewable sources, such as solar, wind, and hydroelectric power generation. Of all those alternatives, the sharpest observed rise is in the utilization of naturally available solar energy. Being a stable and consistently available source of clean energy, solar energy has the significant potential to cater to the ever-increasing world electricity requirements [1]. Keeping in mind the sustainability paradigm, this should be achieved in a technically feasible, cost-effective, socially acceptable, and environmentally reasonable way. The gradual transition to energy production from non-renewable sources to energy from renewable sources requires, in particular, attention to the appropriate dynamics of change of the energy mix of specific countries and its economic and environmental effects. According to Adebayo et al. [2], who investigated the case of the energy mix in Japan, the intensity of the transition to a larger share of renewable energy sources is crucial for reducing GHG emissions, which on the other hand, can influence future economic growth.

While taking into account renewable energy needs, the International Energy Agency (IEA) is calling for an energy revolution. The IEA released a roadmap in which it set up a goal for net-zero carbon dioxide (CO₂) emissions in the energy sector by 2050. The suggested pathway to obtain this challenging goal assumes, among other things, scaling up solar and wind energy production in this decade, reaching annual additions of

630 gigawatts (GW) of solar photovoltaics (PV) [3]. The International Renewable Energy Agency (IRENA) predicts that the share of renewable energy in the primary energy supply will grow from less than one-sixth today to nearly two-thirds in 2050. On the demand side, electricity is predicted to be a primary carrier of energy, with its final consumption being near a 50% share by 2050, and renewable power will be able to provide 86% of the power demand [4]. In this revolution, there is crucial importance placed on technology development and diffusion that allow the implementation of global policy requirements aimed at increasing the utilization of renewable sources of energy [5].

Solar power technologies for sustainable and clean electricity generation are considered one of the most promising alternatives for application on a global scale. As reported by IRENA, in 2010–2019, the cost of solar PV production dropped globally by 82%, mainly as a result of more efficient technologies [6]. The costs of local energy-storing systems also dropped [7]. This made solar energy production competitive with traditional power generation and ensured broad diffusion. However, among the constraints for its increased production is land area needed for it to be able to replace coal or natural gas-fueled power stations. It needs to be stressed that PV panels require large production areas, and these are not always available due to competing land uses, such as industrial, residential, agricultural, and environmental uses [8,9]. Additionally, as claimed by Oudes and Stremke [10], solar power plants transform the existing landscapes and, as further indicated by Picchi et al. [11], they also impact ecosystem services. Therefore, due to its large land consumption, PV energy production is challenging from economic, social, and environmental perspectives, as an activity with many tradeoffs [12,13].

One possible solution to this problem that researchers have discussed is to allocate marginal land for solar energy production. Milbrand et al. [14] defined marginal land as “... areas with inherent disadvantages or lands that have been marginalized by natural and/or artificial forces. These lands are generally underused, difficult to cultivate, have low economic value, and varied developmental potential”. According to these authors, solar technologies present the best opportunity to capture value from marginal land and increase their development potential. Hoffacker et al. [15] identified different marginal land types for solar siting: Built environment, salt-affected land, contaminated land, water reservoirs, and others. They claim that each of these land types has the potential to create synergies between land and solar energy development. However, as stressed by some, e.g., Howard et al. [16] or Cialdea and Maccarone [17], marginal agricultural land, i.e., land with low agricultural productivity, has the highest potential for photovoltaic installations allocation and solar energy production. There is common agreement among scientists and policymakers that agriculture has a seemingly high potential for PV power generation due to different options to install PV on land or farm buildings [18].

At this point, it needs to be highlighted that although the transition to renewable energy will intensify the global competition for land, especially for agricultural purposes, the potential impacts of solar energy production seem not to be addressed enough in the literature. Existing studies focus mainly on the opportunities created by agrophotovoltaic solutions. Cho et al. [19] claim that solar energy installations and agricultural crop cultivation could simultaneously operate on the same land, both with economic justification. However, as investigated by Sacchelli et al. [13], there exist tradeoffs while making decisions about the sole utilization of land for energy or food/feed production. The constraints are related to landscape maintenance, morphological variables, specialization, and crop yields. Case studies confirmed that the coexistence of agriculture and renewable energy production is possible. They recognized roof-mounted or umbrella-shaped facilities using a photovoltaic system as new alternatives to conventional PV plants [20] with many positive direct and synergy effects, such as economic profitability, electricity production for self-consumption, or wildlife benefits [21].

Additionally, ground-mounted PV installations located on arable or grazing lands have been tested as another possible alternative. The results of such experiments are promising, especially for farmers, showing economic benefits [22]. Feasibility studies also

highlight several risks connected to investment capacities, energy storage and grid infrastructure availability, biodiversity enhancement, or social limitations [23,24]. The studies also show that agrophotovoltaic installations change agricultural landscapes [25] and can potentially disrupt ecosystems [26] through reduced agricultural production [27]. Studies also identified several drivers that lead to farmers' decisions and show the role of policies that facilitate such changes in agricultural land utilization [18,28]. Policy interventions are crucial, concerning complex issues of climate change, agricultural land scarcity, and food security. According to Gomiero [29], new models need to be promoted to provide key social, economic, and environmental safety objectives. Pretty and Bharucha [30] suggest that sustainable intensification of agricultural production—thanks to which the land could be used optimally in a local dimension—provides food and energy-production opportunities.

However, only a few studies have investigated marginal agricultural land utilization for solar power production, through the sole allocation of PV installations. The knowledge obtained from these studies shows the importance of the different perspectives—energy-centric, agricultural-centric, or agricultural–energy-centric—in search of the benefits or constraints [31]. Leirpoll et al. [32] indicate several constraints: Landscape, local, environmental, and socio-economic, in the search for optimal coexistence of agricultural production that is possible on marginal lands and solar energy production. As part of that, Milbrandt et al. [14] report the importance of the availability of PV technologies to facilitate the farmer's decisions, and Maye [33] pays attention to the environmental impact of the life cycle of PV infrastructure.

Bearing in mind the growing importance of solar energy production on marginal agricultural land, a key question arises regarding how to assess the efficiency of the decision to install such PV operations, in a way that will satisfy both private and public expectations.

Caputo et al. [34] present a nexus approach to decision-making in cases that affect food production, energy, water, and societal effects. Our study considers most of these aspects by analyzing the economic value of the different impacts in the case of solar PV field development. Spyridonidou et al. [35] present a planning framework for solar and wind power projects that incorporates many of the aspects mentioned above. However, their model does not consider the economic efficiency of the different choices from the private and social perspectives. Thus, in this study, we ask the following question: What are the conditions under which converting agricultural land to solar power production is economically efficient, both from the landowner's perspective and a social perspective? In our study, we aim at addressing that existing gap in the literature, and in doing so, help with better decision-making by both private and public entities. The analysis in the paper compares two scenarios: The status quo with fossil fuel electricity generation, resulting in GHG emissions, but also with more land in agricultural production, and the scenario with solar power generation on marginal agricultural land.

Our goal is to create a tool that will help farmers and policymakers forecast the economic efficiency of solar power installations on agricultural land and other open spaces. This will be achieved by looking at the decision to produce solar power on agricultural land at the margin, i.e., the profit or net benefit from the last hectare of the lowest-productivity land owned by the farmer. The paper brings into the existing body of knowledge a complex and systemic analysis of private and public perspectives of decision justification for installing solar installations on marginal agricultural land, along with empirical evidence from a representative case study, a field in Israel.

1.1. Climate Change Effects in Israel

Climate change is already affecting Israel, and its effects are expected to increase in the future. Mean annual temperatures have already increased by 1.5 °C in 2020 and are expected to increase by an additional 1 °C until 2050. By 2100, it is forecasted that the overall increase in temperature will be 3–5 °C, depending on the emissions scenario used (RCP4.5 or RCP8.5) [36]. The expected changes in precipitation are a significant decrease

in the center and North parts of Israel, reaching up to a 40% decrease in autumn, fewer precipitation days, and more extreme weather events that could lead to floods [37]. The southern, more arid region could potentially experience an increase in precipitation.

These processes have an effect on the agricultural sector in Israel that will become more pronounced as the changes described above intensify. Haim et al. [38] show that some crops such as wheat, grown mainly in Southern Israel, might benefit from the expected changes. Other crops that rely on a more humid climate, such as cotton, will experience decreases in yield and net revenue. Zelingher et al. [39] forecast a partial abandonment of agricultural land, and a shift to production in controlled environments such as greenhouses.

Experts predict that climate change will also influence biodiversity in nearly all ecosystems, mainly due to the changes in temperature and precipitation, with some of these effects already evident in Israel [40]. The abandonment of agricultural lands and their potential conversion to built-up land poses an additional threat of habitat reduction and fragmentation for different species. Solar power production on (former) agricultural land could potentially aggravate the problem if these installations prevent the free movement of animals and the growth of native plant species. Hence, to determine the economic efficiency of solar power production on marginal agricultural land, we include the value of (potentially) lost biodiversity on that land.

1.2. Climate Change Policy in Israel

Israel has ratified the Paris agreement on Climate Change in November 2016. It has submitted its Intended National Determined Contribution (INDC) that promises to reduce per capita greenhouse gas (GHG) emissions to 26% below their 2005 level by 2030 [41]. Given Israel's relatively high rate of population, with a projected population growth of 36–51% between 2015 and 2035 [42], this does not necessarily mean a reduction in overall GHG emissions. In 2017, Israel's government decided on a goal of 10% energy production from renewable sources in 2020. This goal was not achieved, with only 6% of energy consumption in 2020 coming from renewable sources [43]. However, the high rate of growth of solar power and other renewable energy installations, 34% annually in 2012–2019, has led the Israeli government to decide, in 2020, on a more ambitious goal of 30% electricity from renewable sources by 2030. Weiss et al. [44] simulated and showed the feasibility of a 100% renewable energy scenario for Israel in 2030, acknowledging that this will need “radical” market designs.

Similarly, Solomon et al. [45] considered seven different energy transition scenarios in Israel, representing a larger class of Sun Belt countries. They show how the goal of net-zero emissions energy is possible by adopting an explicit pro-solar PV policy and/or using a GHG emissions price. Our study will include the gain to society from reducing GHG emissions as an essential component of the value created by solar power generation.

Israel's unique situation concerning its neighboring states has added two additional geopolitical goals to the renewable energy discourse and policymaking: Energy independence, since it cannot rely on energy supply from some of its hostile neighbors, and cooperation in energy production and supply, supposedly leading to increased economic growth through trade in renewable energy [46].

Additional renewable energy in Israel faces other challenges as well. One example is congestion in the electricity transmission network, because of the recent rise in solar installations [47]. The immediate solution to this problem is reducing energy production from conventional electricity sources, but this requires new agreements with the producers that own these sources.

1.3. The Response of the Agricultural Sector

In the past decades, the agricultural sector in Israel and other developed countries has been subject to processes that lead to rural households' diversification of income sources. These processes include a deterioration in terms of trade for agricultural products, with rising costs of inputs and a relative fall in the price of outputs; increased efficiency in the agricultural sector, leading to reduced demand for labor and food surpluses; and an overall

decline in the importance of agriculture as a source of income [48]. The share of agriculture in Israel's GDP has been declining, and in 2020 it was 1.1%, compared to 4.8% in 1980 [49].

Diversification has led to an increase in non-agricultural land uses such as retail, storage and hospitality, and to the household members looking for employment off-farm [50]. Since 2002, the year the Israeli government decided on the first renewable energy production target of 2% by 2007, another source of income for farmers is solar power generation on rooftops and fields [51].

Agricultural land is converted to other uses, including solar power generation, according to its agricultural productivity. The most unproductive land—the marginal land—is converted to non-agricultural uses first. In this paper, we model the decision faced by agricultural landowners by including the opportunity cost of agricultural production on land converted to a PV installation. The opportunity cost is the value of the alternative use of the resource, in this case, agricultural production.

1.4. Renewable Energy Regulation in Israel

Agricultural fields are not the only option for large-scale solar power production in Israel. The current policy of planning authorities in Israel, whose permission is needed to build large solar projects, is that permits are not given while there is still a potential for rooftop solar power generation on large buildings owned by the landowner [52]. This decision is backed by research showing that in the long run, up to 32% of Israel's electricity consumption could be generated on available rooftop areas [53].

Planning authorities also prioritize building solar power facilities on land adjacent to land meant for buildings or other development; building these facilities on detached open space has a low priority. The guidelines also state that the committee will prefer “plans that maintain the agricultural appearance and use and correspond to the rural texture in the district and the surroundings of the plan” [52]. As a result, the land allocated to solar power installations needs to be of low agricultural value and have a low value for future residential or commercial development. The latter could be overcome if PV facilities do not require irreversible infrastructure changes to the land on which they are built.

2. Methods

2.1. Conceptual Model

The problem of deciding if and how much land to allocate from agricultural production to solar PV production is modeled with a constrained maximization setup, used in many microeconomic applications, e.g., [54,55]. Our model differs from other works that have looked at land allocation between agriculture and solar power, e.g., [56] by explicitly adding the amenity value of land and the value of biodiversity. We solve the maximization problem using the Lagrange multiplier method.

2.1.1. Private Profit Maximization

The decision to divert land from agricultural production to solar energy production will result from profit maximization by the landowner. Assuming that regulations allow the construction of such installations and that climate conditions are favorable, as they are in Israel, the landowner's problem can be written as:

$$\begin{aligned} \max \pi = & P_{ag} \cdot Q_{ag}(L_{ag}, \theta, T) + P_{el} \cdot Q_{el}(L_{el}, T) - TC_{ag}(L_{ag}, \theta, T) - TC_{el}(L_{el}, d) \\ \text{s.t. } & L_{ag} + L_{el} = \bar{L} \end{aligned} \quad (1)$$

Table 1 explains the notation used in the preceding equation and throughout this section.

Table 1. Notation used in the conceptual model.

Symbol	Meaning
π	Profit of the landowner
P_{ag}	Price of agricultural product
Q_{ag}	Quantity of agricultural production
L_{ag}	Land in agricultural production (hectares)
θ	Agricultural productivity of land
T	Index of climate conditions (higher values are higher temperatures and lower precipitation)
P_{el}	Price of electricity (feed-in tariff, per kWh)
Q_{el}	Quantity of electricity produced (kWh)
L_{el}	Land with solar power production (hectares)
TC_{ag}	Total cost of agricultural production
TC_{el}	Total cost of solar power production
MC_{ag}	Marginal cost of agricultural production on an additional hectare
MC_{el}	Marginal cost of solar power production on an additional hectare
d	Distance of solar installation from electricity grid (km)
$\bar{L}$	Total amount of land owned (hectares)
SCC	Social cost of carbon (per kWh of electricity produced from natural gas)
α	Amenity value of hectare of land in agricultural production
γ	Loss per hectare due to fragmentation of ecosystem by solar power production

We assume that production increases with the quantity of land allocated to an activity, i.e., $Q_L' > 0$, and that costs also increase with land $TC_L' > 0$. The landowner maximizes her profit by choosing the values of L_{ag} and L_{el} , i.e., allocating her land between agricultural production and solar energy production. Maximization of the profit function with the Lagrange method with respect to L_{ag} and L_{el} and the multiplier λ leads to the following first-order conditions (FOCs):

$$P_{ag} \cdot MP_{ag, L} = MC_{ag} + \lambda \quad (2)$$

$$P_{el} \cdot MP_{el, L} = MC_{el} + \lambda \quad (3)$$

The FOCs show that the value of the marginal product of the last hectare of land in agricultural production is equal to the marginal cost of production on the last hectare of land and the shadow value of the land; similarly, the marginal product of the last hectare of land in solar energy production equals the marginal cost of energy production on the last hectare of land. The FOCs also show that the profit from allocating the last hectare of land to either agricultural or solar energy production must be equal; otherwise, profits can be increased by allocating that hectare to the higher net value activity.

Hence, we predict that if a landowner has the opportunity to allocate some of her land to solar production, she will do so by assigning her lowest-productivity agricultural land to that activity. The effect of climate change, either current or expected, is uncertain and depends on the kind of crops grown and its impact on markets through the price P_{ag} .

Land that is more distant from the electricity grid will be less profitable in solar energy production due to the additional costs that this entails.

2.1.2. Social Welfare Maximization

The landowner's profit is included when considering the social perspective of the land allocation problem. In addition, social welfare includes external costs and benefits that do not influence private decision-making. The sustainability of agricultural production is not necessarily a consideration for the landowner since inter-generational aspects are not always considered. However, they cannot be ignored when considering the welfare of the

entire population, not only agricultural landowners. Society's net benefit maximization problem is:

$$\begin{aligned} \max NB &= \pi + SCC \cdot Q_{el}(L_{el}, T) + \alpha \cdot L_{ag} - \gamma \cdot L_{el} \\ s.t. \quad &L_{ag} + L_{el} = \bar{L} \end{aligned} \quad (4)$$

This extended problem includes the benefit to society from reducing GHG emissions resulting from the solar energy field, the value of amenities such as agricultural view resulting from agricultural production, and the damage to biodiversity when solar energy installations damage ecosystems and cause habitat fragmentation.

The first-order conditions of the extended problem, obtained using the Lagrange method, are:

$$P_{ag} \cdot MP_{ag, L} + \alpha = MC_{ag} + \lambda \quad (5)$$

$$(P_{el} + SCC) \cdot MP_{el, L} = MC_{el} + \gamma + \lambda \quad (6)$$

Including these considerations in the social perspective can potentially change the amount of land allocated between the two activities in the optimal case: A higher SCC will make solar energy production more valuable, but a higher amenity value of agricultural land can make that activity more worthwhile. In addition, the potential damage to ecosystems from habitat fragmentation and damage to ecosystems in the case of solar energy production means that in some cases, these considerations could lead to a lower amount of solar energy production.

After performing the single-period calculations shown above, we will also conduct a multi-period cost-benefit analysis with a time horizon corresponding to the project's expected life. The following formula will be used for the calculation of the net present value (NPV), the difference between the present value of benefits and the present value of costs:

$$NPV = \sum_{t=0}^T [(B_t - C_t) \cdot (1 + r)^{-t}] \quad (7)$$

In this formula, T is the time horizon in years; B_t is the benefit in year t ; C_t is the cost in year t , and r is the interest rate used in the analysis. Higher values of r denote higher uncertainty and risk.

2.2. Empirical Methodology

In our analysis, we will estimate the necessary conditions for maximum profit for the landowner and a maximal net benefit for society derived in the conceptual model. This will be done using data from a solar power installation case study in Northern Israel, a representative example of a large-scale PV project (≥ 10 MW). Many more such projects are planned in the near future due to the Israeli government's decision to reduce carbon emissions from the electricity sector by 85% from 2015 levels by the year 2050 [57].

The values of the parameters in the model will be obtained from different sources: Actual cost and price data received from the owners and operators of the solar field, academic articles and reports for non-market values, and personal communications with stakeholders.

2.3. Data

The solar field we examine in this study was built in 2020 on 11 hectares, with a production capacity of 10 MW. The landowner in this case is a cooperative village, a kibbutz, that contracted with a renewable energy company. The company leased the land from its owners for 23 years, which is the maximum period allowed by Israel's land authority regulations for such contracts. The landowner does not assume any of the construction costs or other related expenses and risks, and is paid an annual fixed sum for the project's life. Figure 1 shows the solar field and its location between almond orchards, with the village that owns it in the background.



Figure 1. The solar power field in Northern Israel. Photo courtesy of Avihu Biali.

The renewable energy company that built and operates the solar power field is a publicly traded (in the Tel Aviv Stock Exchange) firm specializing in such installations. This fact enables us to obtain cost data and the price of electricity from the firm's announcements to the stock exchange.

Total agricultural land owned by the kibbutz that includes field crops and orchards is 330 hectares. Hence, the current solar installation takes slightly more than 3% of the total agricultural land area. The land where the facility was built was considered unsuitable for field crops and orchards because of severe drainage problems. These do not pose a problem for the solar installation but make the land unproductive for agriculture. Our analysis conservatively assumes that the land is not entirely unproductive, meaning that it could be used for almond orchards. We obtained data on agricultural costs and income from two sources: The manager of the farming operations of the village and the official input–output calculations published by the Israeli Ministry of Agriculture and Rural Development.

The location of the solar power field was selected from 8 possible alternatives in the area seen in Figure 1. The criteria for selection and approval of the installation site by the landowners and the authorities were low agricultural productivity, zoning restrictions, amenity value of the landscape, ecological significance as a wildlife corridor, and possible damage to archeological sites found in the area.

The consulting firm that provided its services to the landowners in the selection process did not perform an economic calculation of the different non-market impacts. Their assessment used a 4-color measure of the severity of the solar power field's impact in each potential location within each category: Green, yellow, orange, and red, from least impact to most impact, respectively.

In our analysis, we use data from reliable academic sources for the values of the non-market impacts of the solar field. The data on the landscape amenity value of farmland per hectare in Israel is from Fleischer and Tsur [58]. They used the contingent valuation method and obtained values between 208 € and 416 € per hectare/year.

The value of biodiversity per hectare comes from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). The organization publishes assessment reports for different parts of the world. Israel is included in its report on Europe and Central Asia. The report contains the non-market values of many functions performed by nature. The median and mean values of habitat creation and maintenance, i.e., biodiversity, are 638 € and 1318 € [59] per hectare per year, respectively.

Since the primary motivation of the shift to renewable energy sources such as solar power is to reduce GHG emissions, we expect the value of the damages prevented to be relatively high. These damages are calculated with the social cost of carbon (SCC). Different

researchers obtained several possible values of the SCC, and we will examine the sensitivity of our results to changes in this parameter. The range of values is between 42 € [60] and 354 € [61] per tonne of CO₂, with 105 € as a value in between the extremes [62].

Since solar power replaces fossil fuel power production, we use the amount of GHG emissions from natural gas electricity production in our calculations, since this represents Israel's most abundant fossil fuel, accounting for the largest share of power production. De Gouw et al. [63] estimate these emissions at 436–549 g CO₂/kWh.

3. Results

The values used in our calculations of both the private profit conditions and the social benefit are given in Table 2. As shown in the conceptual model (Equations (1) and (4)), all the parameters of the private profit maximization problem are also in the social benefit problem.

Table 2. Values used in the empirical application.

Description	Value (€/Hectare/Year)
Net income to landowner from agriculture	2000
Net income to landowner from solar power production	6800
Landscape amenity value	208 to 416
Biodiversity value of agricultural land	638 to 1318
Social cost of carbon (assuming 500 g CO ₂ /kWh)	23,360 to 238,950

3.1. Profit Maximization

The net income to landowners from the highest-value agricultural crop, currently almond orchards, is 2000 € hectare/year. This is a relatively high value. Other marginal lands could have no value in agricultural production, i.e., 0 € hectare/year. The rate at which the renewable energy firm sells the power to the grid is 0.05 €/kWh. This means an income of approximately 67,500 €/hectare/year. The firm pays the landowner 75,000 €/year for the project's life, i.e., a net income of approximately 6800 € hectare/year, or 4800 € hectare/year when considering the opportunity cost. It is clear what a landowner will be inclined to do as a profit maximizer when choosing between agricultural production and leasing the land to the renewable energy firm—the latter one.

When looking at a longer time horizon, that of the life of the project or the contract with the renewable energy firm, which in this case is 23 years, the NPV per hectare is 55,000–66,000 €, using discount rates of 5–7%. Lower discount rates, reflecting a lower risk of the project or lower capital costs, will result in even higher sums.

3.2. Social Welfare Maximization

Using the values shown in Table 2 for the landscape amenity value and biodiversity value per hectare/year, we see that the upper bound of the annual value of a hectare in agricultural production from society's point of view is 2000 + 416 + 1318 = 3734 €. This is still not high enough to justify giving up the higher value of the land in solar power production. Adding the savings in GHG emissions resulting from substituting natural gas power production with solar power tilts the inequality even more in favor of the solar field.

To find the SCC prevented by a hectare of solar power production, we multiply the amount of GHG emissions from natural gas electricity production, which is 412–549 g CO₂/kWh [63,64]. Assuming a social cost of carbon of 354 € per tonne of CO₂ [60,61,63], 1500 MWh produced per MW installed, and 0.9 MW per hectare, this translates to 23,360 € to 238,950 € hectare/year of avoided climate change damage, depending on the values used.

Thus, the annual net benefit of a hectare of solar power production is between 26,426 and 244,904 €. Longer time horizons, such as the project's life of 23 years, mean a social NPV of 297,879 € to more than 3.3 million € per hectare. The calculations performed are shown in Table 3. We also show the minimum and maximum social welfare values. The

minimum values are obtained with the lowest benefits and the highest costs, and the maximum values are obtained with the highest benefits and lowest costs.

Table 3. Social welfare calculations with minimum and maximum values.

Description	Minimum Value (€/Hectare/Year)	Maximum Value (€/Hectare/Year)
Benefits		
Net income to landowner from solar power production	6800	6800
Social cost of carbon	23,360	238,950
Costs		
Net income to landowner from agriculture	0	2000
Landscape amenity value	208	416
Biodiversity value of agricultural land	638	1318
Social welfare		
Benefits—Costs	26,426	244,904
NPV—23 years—5% interest rate	356,449	3,303,406
NPV—23 years—7% interest rate	297,879	2,760,604

The profits and social welfare values obtained in our analysis are compared in Figure 2. It is evident that the conversion of marginal agricultural land is efficient when adopting the landowners' perspective, but even more so when adopting a social perspective. The minimum private profit value reached 4800 €/hectare/year, while the maximum was 42% higher and reached 6800 €/hectare/year. Concerning social welfare, the sensitivity analysis showed a difference between minimal and maximal values of more than nine times (819%) from 26,646 €/hectare/year to 244,904 €/hectare/year.

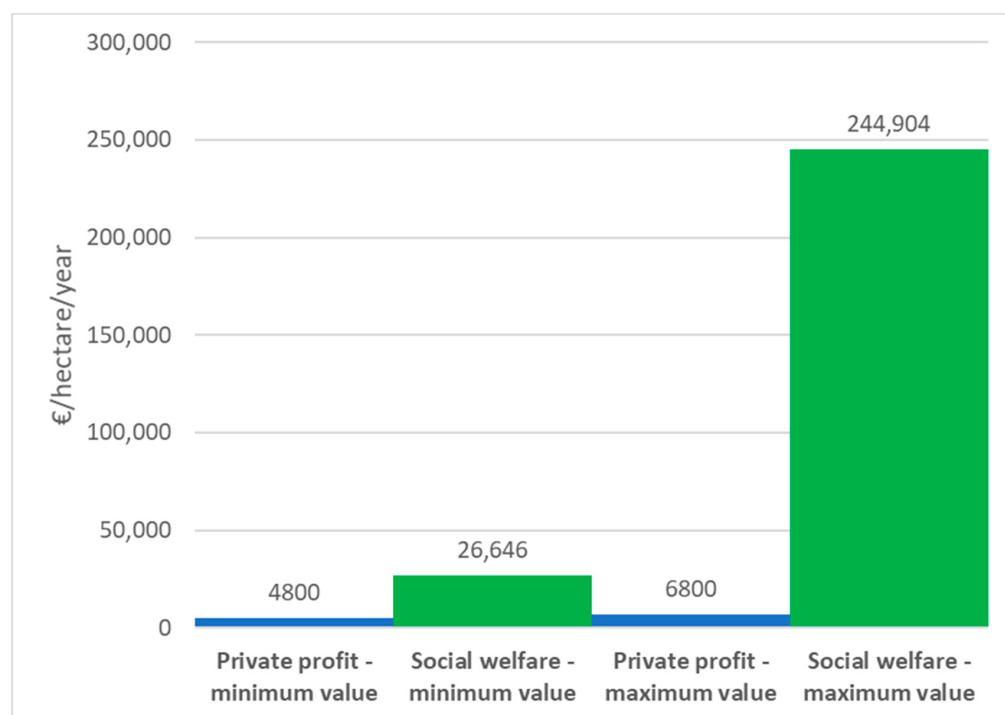


Figure 2. A comparison between annual private profit and annual social welfare of solar power production on one hectare of land.

4. Discussion

The results of our analysis show that as long as climate change is the leading global environmental and societal concern, substituting agricultural land of marginal productivity with solar fields is beneficial both to landowners and to society. This considers a case study of a small solar power field in Israel, where climate conditions make solar power the lowest-cost option for electricity generation. The conclusions might be different in other locations. Furthermore, Capellán-Pérez et al. [65] showed that land-use requirements and solar radiation impact the effectiveness of solar renewable energy production on marginal lands in different countries. Nevertheless, our methodology can be helpful also for those cases.

It is evident from our analysis that the conversion of marginal agricultural land is efficient when adopting the landowners' perspective, but even more so when adopting a social perspective. The latter is associated with the provisions of public goods. Zavalloni et al. [66] paid attention to the importance of the provision of socio-environmental public goods, showing the relationship between public goods provision and land use, as well as their societal value. Therefore, it is important to search for the welfare composition that considers private agricultural income and public good benefits.

The fact that converting agricultural land to a solar power production facility reduces the risk that farmers face in agricultural operations makes such an option, when available, preferable to many crops, certainly to agricultural commodities, as is also reported by other researchers. As part of economic risk reduction, Li et al. [67] indicate that the willingness to change and adoption behaviors of farmers depend on photovoltaic investment costs. However, Ghazeli and Di Corato [68] showed that solar installations reduced the uncertainty in agricultural production.

Changing the assumptions about the non-market value of land can change the results of the analysis. When considering the conversion of non-agricultural lands, such as wetlands or forests, to solar power production, the viability of solar power production might not be straightforward. In those cases, the importance of the land for carbon sequestration, maintenance of biodiversity, landscape, recreation, and other ecosystem services can tip the results in favor of maintaining the land in its current state. Sutherland et al. [69] claim that environmental motives play an important role in decision-making by farmers and are one of the critical factors for policymakers' decisions for supporting such actions.

On the other hand, although Amaducci et al. [70] showed that PV installations could be a valuable system for renewable energy production on farms without negatively affecting land productivity, one also needs to take into account growing food security concerns. Those concerns are rising, also due to possible disruptions to global markets, such as those experienced in 2020 [71]. In such a case, policymakers could become reluctant to give up agricultural production, even on relatively marginal land. It is also possible that in such cases, farmers would also not be willing to enter long-term commitments that could increase their uncertainty in farm profit generation.

5. Conclusions

Global actions towards more sustainable energy production from renewable sources form a movement that can already be recognized as an energy revolution. This revolution is significant from the scope of changes but relatively slow from the perspective of their implementation. Nonetheless, it is taking place. One of the most crucial changes is the use of solar radiation as a source of energy production. PV installations are also built in rural areas, where tradeoff questions arise regarding land allocation between agricultural and energy production. The farmer or the landowner is the final decision maker and needs to consider the short- and long-term effects of what they will decide. Such dilemmas are crucial, especially in marginal agricultural lands, where the costs of agricultural production and the economic gains from solar installations are uncertain. The farmers' dilemma should

also be viewed as part of a social welfare problem that includes additional factors such as ecological and aesthetical values of the competing land uses.

The analysis presented in this paper regarded one PV installation on marginal agricultural land in Israel. The results show that the higher economic gains justified the landowners' decision to install a photovoltaic system. Furthermore, from the social point of view, regarding carbon sequestration, biodiversity enhancement, or land productivity, the analysis favors the investment in photovoltaics on marginal agricultural land. The analysis performed in this paper can be readily applied to future projects in Israel and elsewhere that involve land use conversion from agricultural use to energy production.

A possible direction for future research could be using life cycle analysis to further examine the costs associated with the different land use options, both solar power production and agricultural production. As technological knowledge in climate change mitigation and renewable power generation and storage advances, options such as carbon storage and sequestration and energy storage could further increase the attractiveness of solar power generation.

The problem investigated in this paper should also be considered in a much broader perspective that takes into account the correlation between the use of resources such as land, water, and energy, and food production. The nexus approach requires special attention to marginal land allocation as lands of this type become valuable resources with rising significance in sustainable and resilient growth.

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